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Opportunities for Sustainable Design and Operation of Clean Spaces:

A Case Study on Minienvironment System Performance

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1. Background

In order to identify and pursue energy efficiency opportunities associated with cleanrooms, it is necessary to understand the design and operation of cleanroom systems for specific contamination control requirements. With the industrial trend toward more stringent cleanliness class and tightening clean spaces, it is vital to understand the design of minienvironment and the operational performance of its systems. A good understanding of such system performance would help to identify opportunities in efficient energy end-use and wise allocation of resources associated with processes or productions that require minienvironments and cleanrooms. This report summarizes a case study on energy performance of a common minienvironment used in semiconductor industry, and discusses the opportunities in saving energy, in particular, the opportunities in achieving efficient operation and design that entails applications of minienvironments.

2. Introduction

A minienvironment is a localized environment created by an enclosure to isolate a product or process from the surrounding environment [1,2]. Minienvironments, often termed "Separative Devices," have been gaining popularity to provide effective isolation for critical contamination control. The purpose of using minienvironments is either to protect contamination-sensitive products or processes by isolating them from the ambient environment and workers, or to protect workers or their environment from exposures to hazardous contaminants by isolating the products or processes, or both. Serving similar purposes, a minienvironment carries a variety of names in different industries and applications, in which materials or processes must be protected from the surrounding environment, or operators must be protected from the activities within the minienvironment. For instance, they are called "gloveboxes" in research laboratories and the defense industry; they are also labeled as "isolators," "separative enclosures or devices," or "barriers" in the microelectronics, chemical, and pharmaceutical industries; in addition, they are commonly named "safety cabinets" in biomedical and healthcare industry. Minienvironments can often introduce filtered air through HEPA or ULPA filters at a high airflow speed (e.g., 90 fpm) in order to achieve the desired pressure difference or unidirectional airflows to maintain specific levels of cleanliness and contamination control [3]. Depending on the actual height of minienvironment spaces, air change rates of the supplied air can be much higher than the air change rates of recirculation air in common cleanrooms that are designed to achieve similar cleanliness classification.

3. Minienvironment Design and Operation

3.1 Minienvironment Design

Minienvironments are designed to have an isolation enclosure, typically operating within a conventional clean space, to provide well-controlled environmental conditions where it is needed for specific processes or activities. Minienvironments are normally smaller clean environments than conventional cleanrooms and may be contained within cleanrooms. The use of minienvironments can provide several orders of magnitude improvement in particulate cleanliness levels. In the semiconductor industry, more and more minienvironments have, in fact, become a requirement as semiconductor device feature sizes are getting smaller, and the shift from manual product movement to fully automated wafer movement are becoming common practice - considering benefits of minienvironment Fab designs over conventional Fab designs. A minienvironment can produce very clean environmental conditions or “mini-atmospheres”, and present physical barriers to protect workers from hazardous materials, or vice versa, to protect process from contamination from the occupants. A common situation is that personnel manipulate tools, processes, and products inside the minienvironment with access devices, which can be as diverse as manual glove systems or automatic robotics systems for handling or transferring products. Overall, the advantages in using minienvironments are to allow better contamination control and process integration, to allow cleanliness-class upgrade required for certain process, to improve safety, and to potentially save costs. In the meanwhile, energy intensity may be shifted from the conventional cleanroom systems to the minienvironments that enclose the specific process. On the other hand, in using minienvironments, energy intensity may be shifted from conventional cleanroom systems to the minienvironments that enclose the specific process. On the other hand, the use of minienvironments requires careful and integrated planning that should consider safety, production (yield), ergonomic requirements, and overall production efficiency. This project addresses the energy performance of such devices and overall impact on energy usage of applying minienvironments in cleanrooms.

3.2 Minienvironment Operation

Minienvironments typically introduce large quantities of filtered air through HEPA or ULPA filters (e.g., at an airflow speed of 90 fpm) in order to achieve the desired pressure difference or unidirectional airflows to maintain required levels of cleanliness and contamination control. Depending on the “height” of minienvironment spaces, the air change rates of the supplied air can be much higher than the air change rates of recirculation air in common cleanrooms that are designed to achieve similar cleanliness classification.

Anecdotal industry experience indicates that in some situations, the design and operation of the overall cleanroom might well remain largely unchanged, and that minienvironments (or isolated spaces) are simply adding another set of air movement and air conditioning, requiring more energy to operate. On the other hand, the potential for energy savings could be achieved if the cleanliness levels are correspondingly relaxed in the surrounding cleanroom space. Although there are papers and guidelines addressing minienvironments’ design, construction, and operation [4,5,6,7,8,9,10], and yields and production associated with deploying minienvironments, there is nonetheless virtually no data available to quantify the energy efficiency of minienvironment systems. To understand actual energy implications of a minienvironment system, it is necessary to investigate energy performance of a typical minienvironment, and understand its potential effects on energy end-use.

4. Case Study

4.1 Purpose and Scope

The main purposes for this case study were to develop an understanding of the key parameters of minienvironment design, operation, and control, to investigate energy performance of the minienvironment air system, and to investigate opportunities in improving its energy performance. The focus of the study was on an air system associated with minienvironment space, as distinct from process equipment used for product manufacturing.

This case study focused on energy performance and electric power usage of the air delivery system of a typical minienvironment in a ballroom setting. The report includes analysis of measured energy performance of a minienvironment' s air system, comparisons of the energy performance of the minienvironment studied with that of a cleanroom, and suggestions of energy savings opportunities associated with the use of minienvironment.

4.2 Approaches and Equipment Setup

The case study was designed to measure airflow rates, electric power usage, and air pressures in the minienvironment under various operating conditions. The conditions measured covered the full range of operating points (airflow delivery) that the minienvironment's air system could handle. The key parameters included the following: electric power usage, airflow and air change rate, pressure difference between the space inside the minienvironment and the space surrounding the minienvironment, and energy performance index (EPI). Electric power usage and power factors of the minienvironment air system were measured concurrently with airflow rates and pressures under the range of testing conditions. Analysis was then performed to investigate the correlations among power usage, airflow, pressure control, EPI, power factor, and the size of exhaust opening.

4.2.1 Electric Power Measurement

The power meter used in this study was a true RMS energy analyzer with an uncertainty of ±3% [11]. The meter records the electric current, voltage, power factor, and actual power supplied to air delivery system for the minienvironment. The power meter was used with 0.01-amp to 10-amp current transducers (HA100 Current Probe, uncertainty ±2%) and voltage transducers was used to measure the electric current, voltage, power factor, and actual power supplied to air delivery system for the minienvironment. Parallel current and voltage transducers were also installed to measure concurrent electric power supplied to the motors of fan-filter units. The power meter used in this study was a true RMS energy analyzer (Powersight, uncertainty ±3%).

4.2.2 Airflow and Pressure Measurement

A VelGrid attached to the electronic micro-manometer [12] measured the average speeds of the airflow delivered out of the face of the fan-filter units (FFUs), which were installed at the ceiling of the minienvironment. The size of individual FFU and HEPA filters was 1 ft by 2 ft. The measurement uncertainty in airflow speeds was ± 3% of reading plus ± 7 fpm from 50 fpm to 2500 fpm. Pressures were measured using a Pitot tube, with a measurement uncertainty of ±2% of reading plus 0.001-inch water column (0.25 Pa) from 0.05-inch water column to 50.00-inch water column (or 0.125 Pa to 12500 Pa). The VelGrid samples 16 points over a 1 ft x1 ft area to determine average airflow speeds. Airflow speed-readings were automatically corrected for the density effect of barometric pressure and temperature. Readings were displayed as local density and true air speeds.

4.2.3 Air Leaks

In normal operation, the accurate control of airflows and pressure difference between minienvironment and the surrounding spaces was realized through accurate system information and controlling exhaust openings. To investigate the relationship among power consumption, airflow, pressure difference, and system efficiency, it was necessary to eliminate unintentional air leaks from the minienvironment and its air system. In this study, the minienvironment enclosure was sealed carefully to avoid leaks and to prevent uncontrollable airflow from the process bay to the chase, or vice versa. During the experiment, we controlled and adjusted the size of opening in the front side of the minienvironment barrier.

4.2.4 Setup Diagrams

Figure 1 Minienvironment

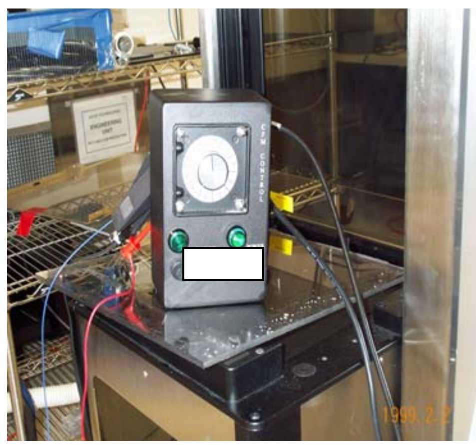

Figure 2 Power measurement setup

4.2.5 Measurements and Data Analysis

The exhaust opening of about 20% of the total FFU surfaces or floor area was initially set while we concurrently measured the maximal airflow rates through FFUs, electric power (Watts) supplied to the FFU speed controller, and the pressure difference between the space inside the minienvironment and the space surrounding the minienvironment. At the 20% exhaust opening, airflow rates through FFUs were then adjusted from zero up to the maximal value so that performance curves can be developed to represent the whole range of actual operation conditions. The inter-correlations among power usage, airflow, pressure control, EPI, power factor can then be analyzed. In addition, a set of parallel measurements was taken for various sizes of exhaust opening. The analysis also includes an examination of the correlation of energy performance indices and other performance metrics of the minienvironment air system with the relative exhaust opening.

4.3 Results

4.3.1 Characteristics of the Minienvironment

The minienvironment in this study was a stand-alone open-loop system, with airflow supplied from the surrounding cleanroom space (Figure 1). The supplied air was filtered through four FFUs, each of which was 1 ft by 2 ft with a depth of two feet. The floor size of the minienvironment was 2 ft by 4 ft with an inner space height of seven feet and seven inches. The supply air was from the top of the minienvironment and there was an opening in the front toward the bottom. The FFUs were integrated with a unidirectional flow shield that was tied to the HEPAs. There was no air recirculation path within the minienvironment; therefore it was an open-loop minienvironment system. The outgoing airflow path allowed uncontrolled mixing with the external environment. In normal operation, a pod was attached to the minienvironment. Such a pod was essentially a box containing a cassette of wafers used in conjunction with a standard mechanical interface (SMIF). The front-open unified pod (FOUP) I/O device was a material handling unit and isolated the cassette of wafers while maintaining the integrity of the wafer environment. The integrated pod transported wafers in and out of the minienvironment without exposure to the surrounding environment.

Four identical 1 ft by 2 ft fan-filter unit (FFU) were used in the minienvironment's air system. Each of the FFUs was designed with a single-phase AC motor with adjustable airflow rates or airflow speeds controlled by a Silicon Controlled Rectifier (SCR) controller.

4.3.2 Fan-speed Controller

Reducing the operating airflow speeds not only can save FFU fan power, but also may lower noise and be beneficial to the operating life of the fan. Normally, the fan speeds could be controlled manually or by sensing the air pressure in the minienvironment enclosure and reducing the fan supply voltage. In this study, fan speeds were controlled manually to measure the key parameters for a range of operating conditions. The fan integrated in the fan-filter units was powered by a single-phase AC motor. The fan speed was controlled via a silicon-controlled rectifier (SCR).

Because the purpose was to develop an understanding of the key parameters of minienvironment design, operation, and control, to investigate energy performance of the minienvironment air system, the supply airflow rates into the minienvironment and the pressure difference were controlled to represent various operating conditions commonly observed in the minienvironment air systems. The concurrent power consumption of the minienvironment air delivery system was measured. The data obtained can be used to develop performance curves representing relationships of power, efficiency, airflow rate, and pressures difference. The range of airflow speeds was from zero to 110 fpm, with the range of pressure difference being zero to 0.3-inch water column. In pharmaceutical applications, the minimal airflow speed is typical set at 90 fpm.

4.3.3 Electric Power and Airflow Rates

Reducing the operating airflow speed not only can reduce FFU fan power, but also may improve cleanliness, lower noise, and improve operating life of the fan. Normally one would expect fan power consumption to increase with an increase in airflow rates. **Error! Reference source not found.** shows that when the airflow speed was less than 95 fpm, total electric power supplied to the FFU increases with the increase in airflow rates. In addition, the rate of electric power increase with the airflow rate goes down with airflows when the airflow speed was below 95 fpm (or 760 fpm), at which the total electric power input reaches to a peak. In contrast, when the airflow speed was above 95 fpm, the total electric power decreases with the increase in airflow rate. This indicates that it takes less fan power for the minienvironment air system to run at a higher airflow rate than it does at a lower airflow rate.

The trends observed in the figure also confirm that with this speed controller, once the initial resistance was overcome, the air delivery becomes easier (and therefore, more efficient) for the system to move the same airflow rate through the air system.

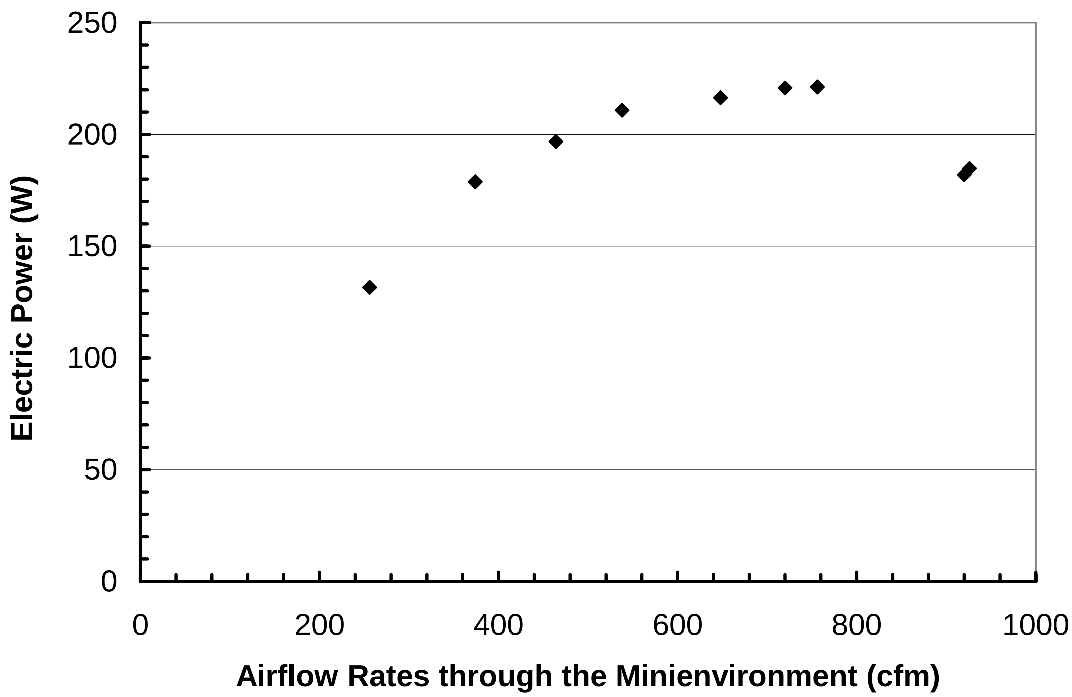

Figure 3 Electric Power and Airflow Rates

4.3.4 Power Factor and Airflow Rate

Associated with the true power consumption, power factor was another metric affecting the power efficiency of the air delivery system. Similar to true power consumption, the figure shows that when the airflow speed was lower than 95 fpm, the power factor increased with CFM in a trend that was close to linear. When the airflow speed was around 95 fpm, the power factor reached a peak at around 0.74. Interestingly, when the airflow speed was higher than 95 fpm, the power factor decreased with the increase in airflow rates. This indicates that when the airflow speeds converged toward 95 fpm, the fan motor power system for air delivery was more efficient in delivering air. The lower end of the power factor was about 0.60, when the airflow speed was about 30 fpm or 110 fpm. At higher airflow speeds (i.e., 110 fpm), the power factor decreased accordingly.

4.3.5 Energy Performance Index

In this study, the energy performance index (EPI) of a minienvironment air system is defined as the total electric power supplied to the fan system divided by the flowrate of the delivered air. A higher EPI means more power is needed for the same airflow rates supplied to and through the minienvironment, corresponding to lower air delivery efficiency in the minienvironment. Figure 4 shows the results in air system's energy performance index, with the EPI ranging from 0.20 W/cfm to 0.42 W/cfm corresponding to the range of airflow speeds from approximately 60 fpm to 110 fpm. This was within or lower than the overall benchmarked range observed in many large cleanrooms (ISO Class 4 or Class 5) [13]. The re-circulation air system efficiency for ISO Class 4 and 5 cleanrooms ranged from approximately 1,100 cfm/kW to 10,500 cfm/kW, corresponding to the approximate range of EPI values of 0.10 W/cfm to 0.90 W/cfm for all recirculation air systems. Compared to the FFU systems in cleanrooms with ISO Cleanliness Class 5 or lower cleanliness classes, the energy performance index of the minienvironment system appeared to be higher, indicating a less energy-efficient air system in the minienvironment. This may suggest opportunities to improve its air systems' delivery efficiency.

The measured airflow speeds corresponded to airflow rates in the range of approximately 460 to 900 cfm, and a positive air pressure inside the minienvironment in the range of 0.01-inch water column to 0.03-inch water column (or 2.5 Pa to 7.5 Pa). By controlling the airflow, a positive pressure was created to prevent introduction of potential contaminants from the surrounding environment. For common airflow speeds ranging from 50 fpm to 90 fpm, the measured EPI ranged from 0.30 W/cfm to 0.45 W/cfm.

In general, the EPI values decreased with the delivered airflow rates. The rate of the EPI decreasing was almost constant - indicating an almost linear correlation between EPI and airflow rates. The trend indicates that the air system EPI value became lower (more efficient in delivering the air) when the airflow rate through the minienvironment increases.

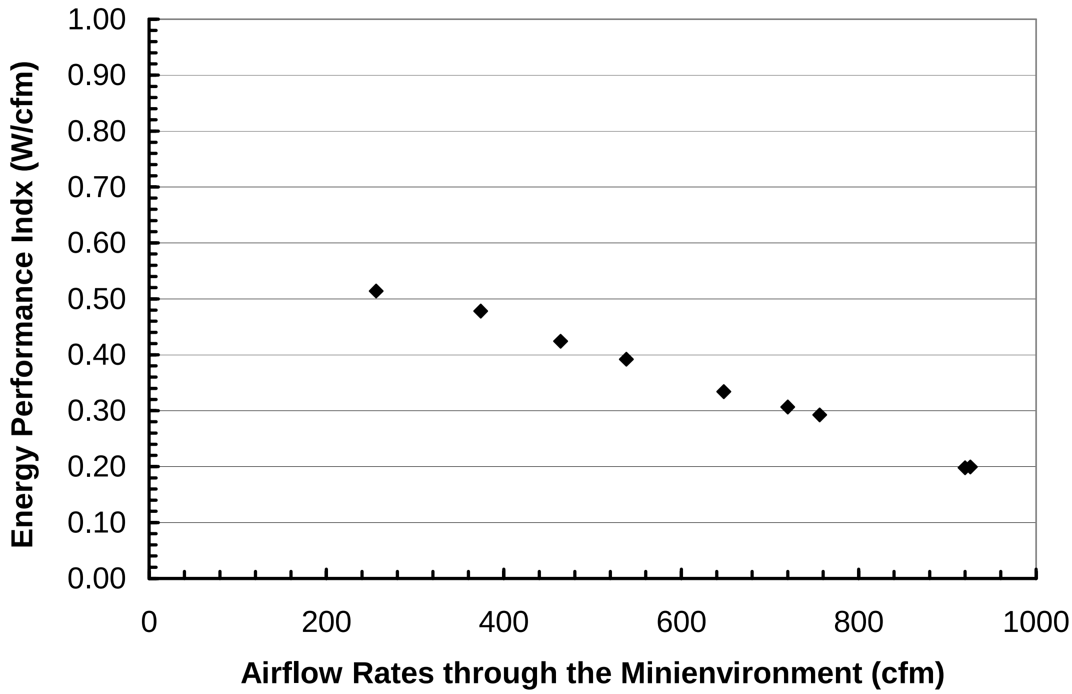

Figure 4 EPI and Airflow Rate

4.3.6 Pressure Difference

The air pressure difference was the difference between air pressure in the minienvironment's internal space and that of its ambient surrounding. The purpose of maintaining a positive air pressure in minienvironment relative to the air in the surrounding spaces was to prevent the less-clean air from being transported to the minienvironment and therefore contaminates the process.

According to IEST CC- RP 028.1 [1], microelectronic minienvironments spanning between process bay and services chase should be designed to maintain a differential pressure, with a typical process-bay pressure exceeding the service-chase pressure by 0.01-inch water column to 0.05-inch water column (or 2.5 Pa to 12.5 Pa). A rule of thumb in the industry is to commonly control the pressure differential with a minimal value of 0.01-inch water column (2.5 Pa) up to 0.03-inch water column (7.5 Pa). However, the ranges seem to be experiential and there is no scientific data to specifically support such ranges.

Figure 5 shows that as expected, pressure-differential increased with delivered airflow rates, and that the increase-rate of pressure-differential was almost constant. This indicates an almost linear correlation between airflow rate and pressure differential between the minienvironment and its surrounding space. A higher airflow produced higher pressure-differential. For example, corresponding to airflow speeds from 50 fpm to 90 fpm, the pressure differential ranged from

0.008-inch water column to 0.02-inch water column (2.0 Pa to 5.0 Pa); corresponding with airflow speeds from 60 fpm to 110 fpm, the pressure differential ranged from 0.01-inch water column to 0.03-inch water column (2.5 Pa to 7.5 Pa).

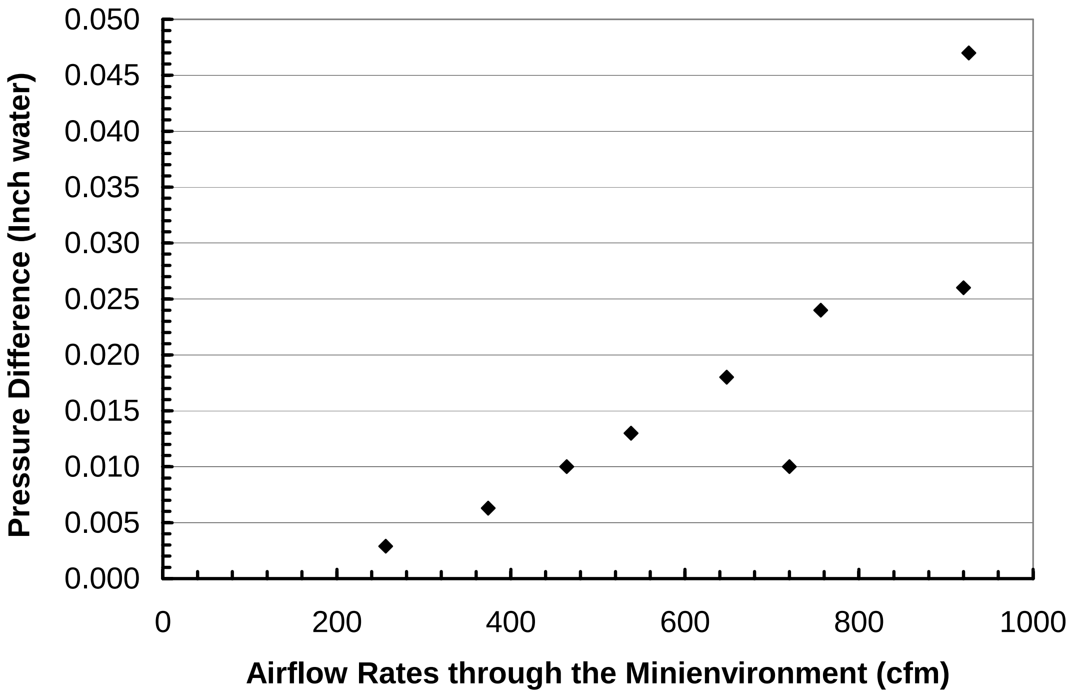

Figure 5 Pressure Difference

4.3.7 Electric Power Density

Figure 6 shows that electric power density changed with airflow speed and pressure differential. Corresponding to the tested operating ranges (30 fpm to 110 fpm) for this minienvironment, power density changed from 16.5 W/ft^2 to 23.0 W/ft^2, with a peak of 27.7 W/ ft^2 when the air speed was 95 fpm.

This range actually fell within the range of fan power density from previously measured ISO Cleanliness Class 4 cleanrooms that was in the range of 16 W/ft^2 to 38 W/ft^2 [13,14]. Given a same airflow speed in general, the power density of the minienvironment tended to be slightly higher than those of cleanrooms of similar cleanliness requirements, especially when the cleanrooms were not fully covered by HEPA filters.

Because of the much smaller minienvironment volume compared to that of full-scale cleanrooms (e.g., ballroom), the amount of airflow rate supplied to a minienvironment was significantly reduced. This result suggests opportunities for a significant overall energy savings potential in through

1) optimization of airflow speeds required in the minienvironment may reduce power consumption of minienvironment while satisfying contamination control; and

2) reduction of the total cleanroom airflow rate by introducing minienvironment due to the vastly smaller volumes of air that must be moved, conditioned, and filtered. The optimization of airflow speeds can be achieved through optimizing fan-filter unit efficiency and the airflow pathway design including exhaust opening.

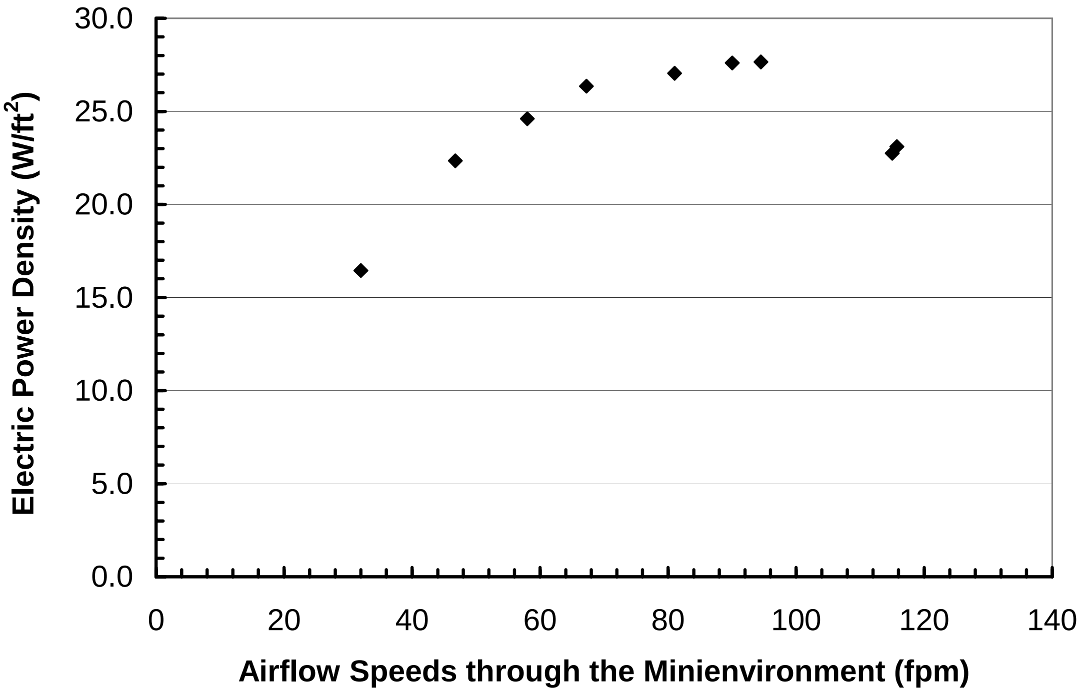

Figure 6 Power Density and Airflow Speeds

4.3.8 Air Change Rates

In semiconductor wafer manufacturing, the air supply for a large "ballroom" with cleanliness of ISO Cleanliness Class 4 or ISO Cleanliness Class 5 was filtered and recirculated at rates as high as 500- or 600- air changes per hour, while the wafer manufacturing only takes place in a relatively smaller area within the whole cleanroom space.

In this case study, the minienvironment typically operated with once-through airflow speeds in the range of 60 fpm and 100 fpm, which was consistent with the airflow speeds commonly observed in conventional large clean spaces. The HEPA/ULPA filter coverage in the minienvironment was 100% while other cleanrooms can have a coverage ranging from 20% up to 100%. If we convert the airflows into actual air change rates for the minienvironment studied, the actual air change rates ranged from 480 to 800 air changes per hour corresponding to the airflow speeds ranging from 60 fpm to 100 fpm. The air change rate range of the minienvironment was higher than the range observed from those of ISO Cleanliness Class 4 cleanrooms, which were in the range of 385 to 680 air changes per hour corresponding to airflow speeds ranging from approximately 60 fpm to 120 fpm [13].

4.3.9 Exhaust Opening

Given that all other conditions were the same, one would expect that the size of air exhaust from minienvironment could affect the resistance in the airflow pathway, airflow patterns and distribution, and pressure differential between inside and the surrounding environment. It would therefore influence the overall operating performance of the minienvironment air system, including power consumption and energy performance index.

In this case study, the exhaust size of the minienvironment air system was controlled to follow a sequence of changes in terms of its relative size to the FFU coverage, or in this case - simply the minienvironment's floor area (i.e., percentage). The relative exhaust size was calculated as the ratio of actual exhaust size to the floor area of the minienvironment.

With the relative exhaust sizes at approximately 10%, 20%, 30%, and 85% of the minienvironment floor area, the power consumption, power factor, EPI, pressure differential, and airflow rates were measured for the maximal airflows for the minienvironment operating at each exhaust size. Among these parameters, power factor, EPI, pressure differential, and airflow rates were plotted against the relative exhaust opening (Figure 7). From the figure, we can see that the achievable maximal airflow rates went up very slightly when the relative exhaust opening increased from below 10% up to 85%. In the meanwhile, the power factors almost were maintained within a range without significant increasing or decreasing trend. The corresponding EPI values did not decrease significantly as the relative exhaust opening increased from 10% to 85%.

The pressure differential however exhibited a significant drop when the relative exhaust opening increased from below 10% to 20%. The pressure differential surprisingly increased when the relative exhaust opening increased to around 30%. This indicates that differential pressure ranges were largely influenced by the relative exhaust opening; therefore, selecting a certain exhaust opening could help in tuning the differential pressures for control purposes.

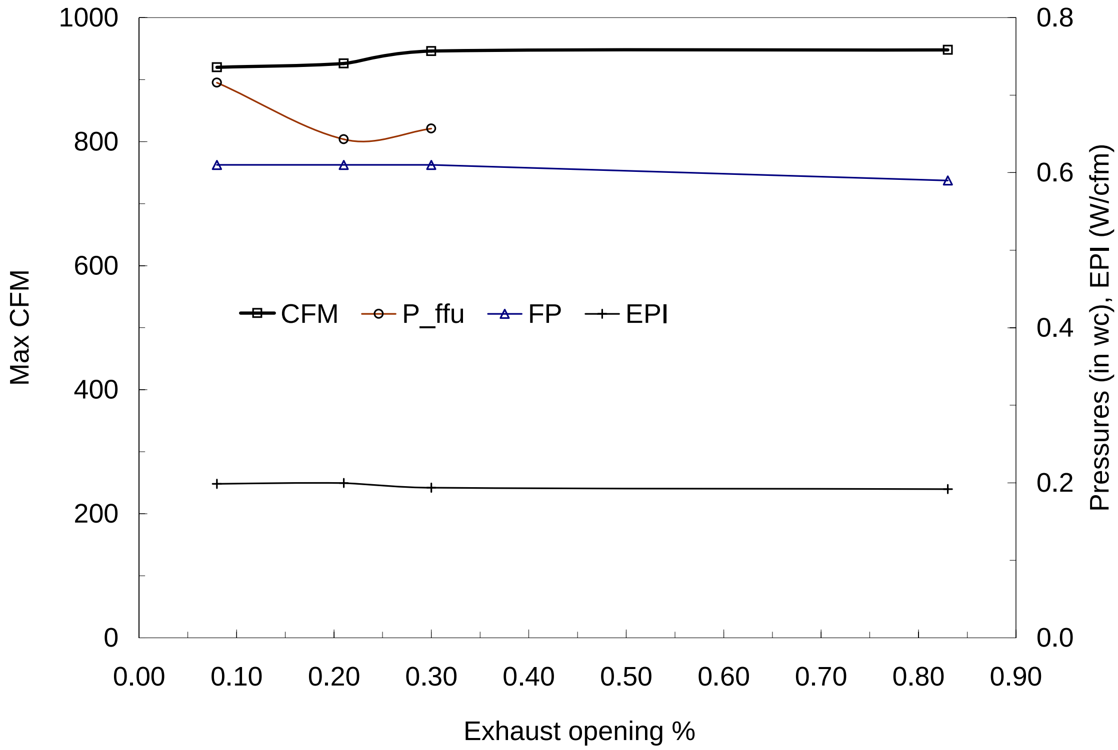

Figure 7 Performance of Minienvironment System as a Function of Relative Exhaust Opening

5. Conclusion and recommendations

Based upon the experimental observation and analysis in this case study, it can be concluded that minienvironment applications largely influence the future design, construction, and operation of cleanroom spaces, depending on their specific contamination control requirements. It is important to determine overall contamination requirements for types of clean spaces through specifying the right cleanliness and control. It is common that designers and users tend to associate higher cleanliness with higher airflows or pressure difference. However, a thorough understanding of contamination control requirements for specific activities is vital because the design, construction, and operation of clean spaces will largely influence the energy consumption as well as effectiveness in contamination control.

Providing measured data to quantify energy performance of the minienvironment, this study shows that the energy performance index of a minienvironment for typical operation tended to be in the vicinity of or higher than that of its counterparts in traditional cleanrooms. In addition, electric power density of the air system in such a minienvironment could be higher than that of normal cleanroom systems. Based upon the analysis, implementing minienvironments as a means of contamination control may produce overall savings in electric power consumption.

A new performance metric was developed in this case study - energy performance index that is based upon electric power usage per airflow rate to characterize the energy efficiency of airflow systems applicable to minienvironments. A lower energy performance index corresponds to a more energy-efficient airflow delivery system. This case study concludes that the energy efficiency of devices used in air systems such as the FFUs and their control mechanism largely affected the overall air delivery efficiency, and could vary largely. On the other hand, the filtration efficiency could be affected by airflow speeds, the design, geometry, and material of filters used in the minienvironment. Optimal contamination control for minienvironments could be realized by regulating airflow rates and air pressure differentials between minienvironment space and its surrounding space to achieve effective and efficient particulate filtration control.

Recommendations from this study include investigating power density as well as energy performance indices of minienvironment as compared to that of traditional cleanroom systems, integration of minienvironments in cleanrooms, and further analysis of savings potential for integrated design, construction, operation, and management of clean spaces.

Last but not the least, there is a need to develop strategies and best practices that can be used by the industry for energy efficiency improvement. Future activities may include providing technical education, interactions and engagement in developing or improving IEST Recommended Practice and design guidelines, and collaboration with industrial leaders such as leading minienvironment suppliers or users. The improvement in energy savings and minienvironment system performance will be beneficial to sustainable development in this sector.

6. Acknowledgement

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